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APPLICATION OF MATHEMATICAL MODELING FOR STUDYING THE STRENGTH PROPERTIES OF FOAMED SLAG GLASS

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The possibility of producing a heat-insulating glass composite material on the basis of slag waste from thermal electric power plants (foamed slag glass) is examined. A series of compositions of foamed slag glass has been developed. The samples obtained were subjected to tests: determination of the water absorption, specific weight, apparent porosity, density, and compression strength. Optimal experiment planning methods were used to study the strength properties of foamed slag glass.

Key words: energy conservation, resource conservation, slag from thermal electric power plants, foamed slag glass, full factor planning, mathematical modeling.

A promising current trend is the development of resource-conserving technologies for new glass-composite construction materials (foamed slag glass) based on technogenic raw material.

Foamed glass is one of the most promising heat- and sound-insulating materials. It can also be used to produce block foamed slag glass, granulated foamed slag glass, and foamed chips. Foamed glass has the following unique collection of properties:

applicability in a wide temperature range;

high water impermeability;

incombustibility;

stable dimensions;

resistant to corrosive media, including acids;

high strength indications;

possibility of wide applications [7 – 9]; foamed glass can be used in construction and apartment and public complexes as universal heat insulation as well as in individual construction, agriculture, power engineering, machine engineering, chemical and petrochemical industries, food, paper, pharmaceutical and other manufacturing.

Slag from the Novocherkassk State Regional Power Plant (SRPP; Rostov Oblast) operating on Donetsk coals was chosen as the object of study and processing. The chemical and phase compositions predetermine the activity of slag. The slag from the Novocherkassk SRPP is ultra-acidic. Such slag has been little studied and there is no demand for it.

The chemical composition of the slag waste from the Novocherkassk thermal electric power plant is as follows (wt.%): 53.0 SiO_2, 20.4 Al_2O_3, 14.2 Fe_2O, 3.7 CaO, 1.63 MgO, 0.68 TiO_2, 1.0 Na_2O, 3.7 K_2O, and 1.45 SO_3.

The plan was to produce foamed slag at the first stage of the investigations, but the slag does not sinter in pure form, so that a decision was made to replace part of the cullet with slag in the foamed glass. As a result a series of compositions of foamed glasses based on slag and ash from the thermal electric power plant was studied. The slag and ash content in all samples was at least 70%. Reactive materials such as borax, soda, chalk, cullet, magnesium sulfate, graphite, and boric acid were used as additives.

Heat treatment was conducted using the classical technology for obtaining foamed glass, which presupposes the following: preparation of finely dispersed mix consisting of glass powder, thermal electric power plant slag and pore former, briquetting of the samples, sintering the mix with simultaneous porization, and fixing the porous structure and removing the temperature stresses. It was found that the rate of heating of the tested samples considerably influences the porization process. The optimal heat-treatment regime was set: the samples were loaded into the furnace at $t = 650°C$, in the furnace t was raised to 950°C in 40 min, soaking at this temperature for 30 min, and cool-down together with the furnace (annealing). Annealing is necessary to remove the residual stresses, so that the sample does not shatter during sharp cooling.

After sintering the samples were subjected to the following tests:

determination of the water absorption when the sample is boiled in water (from 3.31 to 84.43%);

determination of the specific mass by a computational method (from 0.26 to 1.91 g/cm^2);

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TABLE 1. Variable Factors in Conventional and Physical Notation

Conventional notation	Variable	Variation limits	Variation interval
X_1	Slag content, wt.%	70 – 80	5
X_2	Chalk content, wt.%	5 – 15	5
X_3	Foaming duration (at t = 950°C), min	20 – 40	10

TABLE 2. Planning Matrix and Response Function of the Physical Variables

Variable factors, %		Response function Y (ultimate compression strength), MPa, with foaming duration X_3, min		
X_1	X_2	20	30	40
70	5	1.03	0.95	0.89
	10	0.93	0.89	0.86
	15	0.87	0.81	0.79
75	5	1.05	0.97	0.96
	10	0.99	0.98	0.94
	15	0.96	0.93	0.91
80	5	2.20	2.18	2.00
	10	2.15	2.10	1.99
	15	2.08	2.03	1.98

determination of the apparent porosity — ratio of the volume of open pores to the volume of the material (from 4.21 to 55.79%);

determination of the density by hydrostatic weighing of the samples (from 0.55 to 1.86 g/cm^2); the approximate thermal conductivity at 0°C, found according to the density index using tables, ranged from 0.14 to 0.70 W/(m · K);

compression strength tests (range 0.04 – 2.76 MPa).

The solution of most problems in the development of new materials with prescribed properties involves complex and expensive experiments. This is also true of the technology being developed for the production of foamed slag glass. Considering the high labor and energy costs as well as the complexity of the composition developed, it is reasonable to use optimal experiment planning methods, which greatly decrease the time and material resources needed to complete the research work.

The STATISTICA system makes full use of modeling methods using structural equations and flexible means of simulation modeling. Dispersion and covariation analysis, which are a subset of the general linear modules in which plans of almost unlimited complexity can be analyzed, are implemented in the dispersion analysis module used. The possibility of prescribing a plan directly, having determined the real variables and the levels of the factors, makes it possible for even not very experienced users of the STATISTICA system to analyze extremely complex plans in this module. An approach based on a model of averages is tacitly used in the module. Fixed or variable covariates are used for plans of any type, and incomplete plans can also be analyzed [9 – 10].

The variable factors (independent variables) were chosen on the basis of the problem posed and a priori data. Their values are presented in Table 1, where X_1 is the slag content, X_2 is the chalk content, and, X_3 is the foaming duration at 950°C.

The quite wide range and variation step for each independent variable are due to fact that all possible variants must be taken into account to the maximum extent possible. The ultimate compression strength (MPa) of the foamed slag glass was chosen as the independent variable (response function).

The planning matrix combined with the experimental results is given in Table 2.

A linear mathematical model of the following form was obtained as a result of the analysis of the experimental results:

$$Y = 14.5134X_1 + 191.8219X_2 - 95.1123X_3.$$

The residual dispersion is 0.17 and the coefficient R-squared of determination is 0.83. Evidently, the smaller the variance of the residues near the regression line with respect to the total variance of the values, the better the model obtained is. The value of R-squared is an indicator of how well the model fits the data (R-squared values close to 1.0 show that the model explains almost the entire variability of the corresponding variables).

To obtain a quantitative description of the differences between the groups of observations modeling of surfaces (plots of the latter were obtained by quadratic smoothing) with respect to different grouping variables was performed and maps of contour lines, which are a projection of three-dimensional surfaces on a two-dimensional plane (plots of surfaces and their projections are displayed in Figs. 1 – 3), were constructed.

The wide selection of 3D-plots, including different XYZ diagrams and spatial plots, made it possible to obtain optimal, for displaying the results, ternary plots of surfaces and surface contours with a description of the squared functional dependence of the variation of the properties of the ready material. Interactive rotation, change of proportions, and perspectives are supported in the 3D representation.

The equations obtained for determining these surfaces have the following form:

$$Y = 114.7011 - 3.144X_1 - 0.049X_2 + 0.0217X_1^2 + 0.0004X_1X_2 + 0.0003X_2^2;$$

$$Y = 111.8061 - 3.077X_1 + 0.0058X_2 + 0.0213X_1^2 - 0.0001X_1X_2 - 0.0005X_2^2;$$

$$Y = 101.3656 - 2.7837X_1 - 0.059X_2 + 0.0193X_1^2 + 0.0008X_1X_2 - 0.0003X_2^2.$$

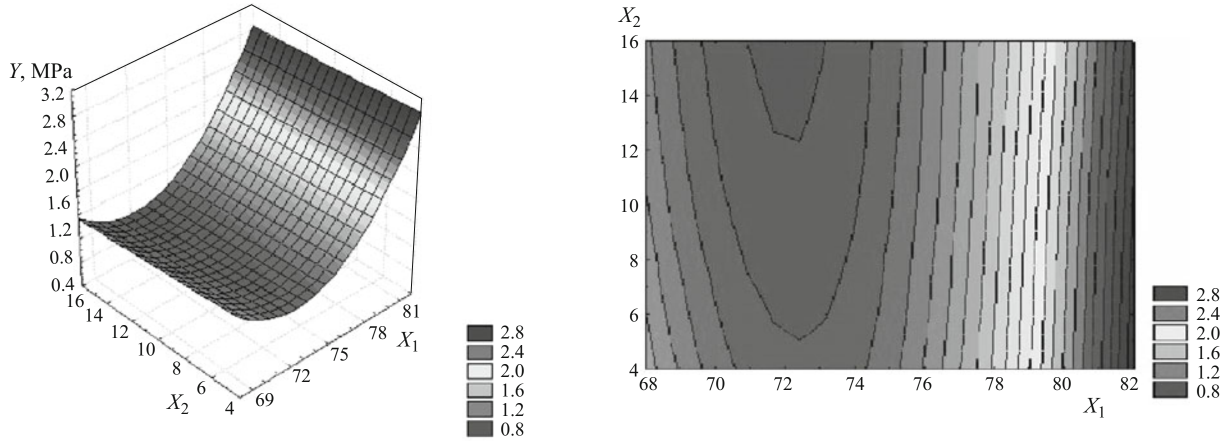

Fig. 1. Variation of the compression strength of foamed glass versus the content of slag and chalk with foaming duration 20 min.

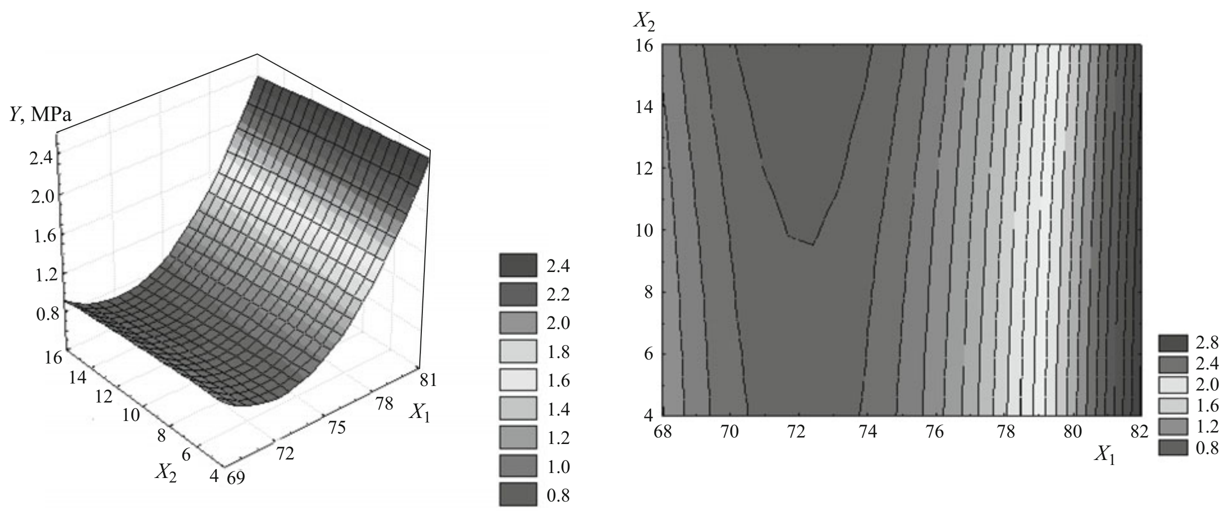

Fig. 2. Variation of the compression strength of foamed glass versus the content of slag and chalk with foaming duration 30 min.

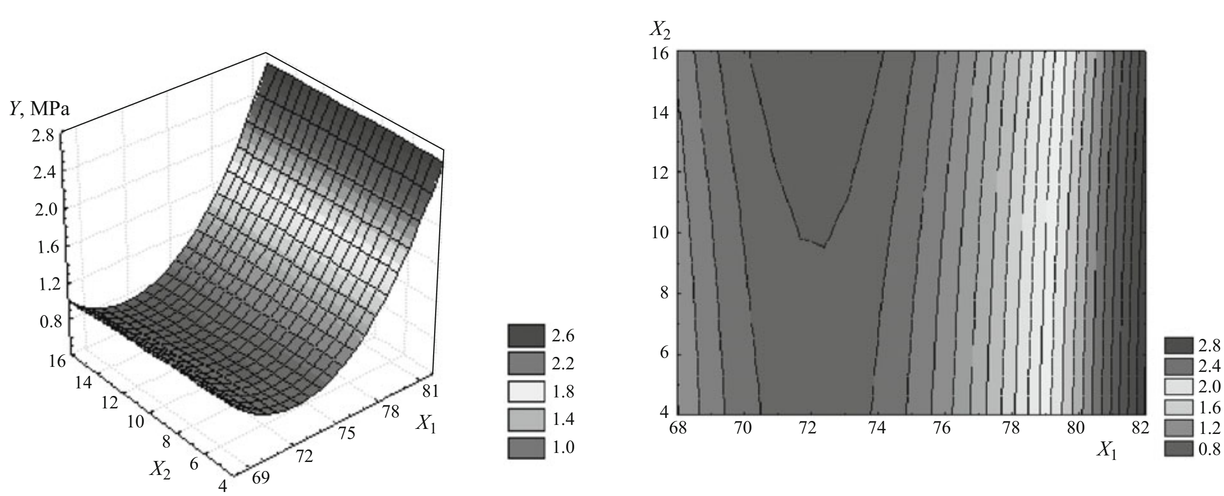

Fig. 3. Variation of the compression strength of foamed glass versus the content of slag and chalk with foaming duration 40 min.

Analyzing the dependences and plots obtained, it can be concluded that the introduction of 80% slag and 0 – 15% chalk into foamed slag glass increases the ultimate strength of the material to 2 – 2.4 MPa with optimal foaming duration about 20 – 30 min. Thus, using together with total factor planning and mathematical analysis of the experimental results the methods of mathematical modeling makes it possible to represent the results with the greatest clarity and to determine further problems to study [9 – 10].

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